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Field assessment of innovative sensor for monitoring of sediment accumulation at inshore coral reefs

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Abstract

Sediment accumulation rate is a frequently required parameter in environmental and management studies, in particular near coral reefs where sediment accumulation can potentially cause severe impact. However, opportunities to obtain accurate sediment accumulation measurements are often limited by a lack of adequate instrumentation, in particular for high temporal resolution monitoring. For instance the traditional use of sediment traps, as the most widespread technique, offers poor temporal resolution (commonly of weeks) besides having significant hydrodynamic shortcomings. Therefore, a new optical backscatter sediment accumulation sensor (SAS) was developed to continuously measure in situ short-term sediment accumulation in sensitive riverine and coastal environments, enabling high temporal and vertical resolution (order of 1 h and with a deposited thickness resolution in the order of 20 μm respectively). This allows investigations of various parameters that influence accumulation: tides, current, waves, rain, or anthropogenic activity such as sediment dumping. This paper briefly describes the SAS and presents three field applications on nearshore coral reefs at Ishigaki Island (Japan), Lihir Island (Papua New Guinea), and Magnetic Island (Australia).

Keywords: Sediment; Accumulation; Coral reef; Optical backscatter; High frequency measurements

1. Introduction

Sediment accumulation rate is a frequently required parameter in environmental and management studies because it is linked to numerous processes of sediment transport and geomorphologic changes in coastal and riverine environments such as beaches, estuaries, river banks, salt- and mudflats, mangroves, and wetlands in general. Sediment accumulation is also of concern near coral reefs where it can potentially cause severe impact, including smothering and death of corals in extreme cases. Sediment accumulation on fringing coral reefs can be linked to a variety of factors including: terrestrial erosion and subsequent sediment runoff; resuspension; or, anthropogenic disposal of sediment at sea. Regardless of its origin, the consequence of such accumulation on coral health has attracted significant scientific and management attention since the mid-70s (review by Rogers, 1990; Anthony, 1999). It is generally accepted that very high rates of sediment accumulation (order of hundreds of $mg\,cm^{-2}\,day^{-1}$) typically lead to smothering and death of the coral polyps (Dodge and Vesnys, 1977; Marszalek, 1981; Stafford-Smith, 1992; Fabricius and Wolanski, 2000), but the impact of low level accumulation is largely debated (Dollar and Grigg, 1981; McClanahan and Obura, 1997; Phillip and Fabricius, 2003). The limit itself between low and high accumulation is poorly defined, partly due to the complex high frequency hydrodynamic interactions and the lack of time series from self-logging instrumentation. Besides, sediment accumulation comprises numerous characteristics such as magnitude, rate, duration and timing that

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contribute to sediment accumulation, adding to the complexity of its measurement. To date, sediment accumulation on reefs has been mostly measured with sediment traps, with only rare examples of other methods published, using sediment tiles (McClanahan and Obura, 1997) or a syringe to collect the accumulated sediment (Lasker, 1980).

One major disadvantage of the widespread sediment traps technique is that they attempt to measure the accumulation rate averaged over the entire sampling period of time, which can be as long as days or weeks. Moreover, traps tend to yield biased results as soon as current occurs, due to hydrodynamics disturbance of the flow around the trap (Hargrave and Burns, 1979; Håkanson, 1989; Lund-Hanson et al., 1997). Although this bias is well known, it is rarely compensated for in flux calculations, mainly due to the difficulty to separate primary and secondary fluxes (i.e. particles that accumulate for the first time as opposed to particles that have been resuspended and re-accumulate). Hence, the interpretation of accumulation data from sediment traps is limited by poor temporal and vertical resolution and cannot resolve short-lived environmental forcings (such as tides, storms, or runoff events), making it difficult to understand the influence of these forcings over coral health.

In this paper we present the application and field trial data of a new instrument called a sediment accumulation sensor (SAS) (Thomas et al., 2002), which is based on earlier design of an upward-pointing optical backscatter sensor (OBS, after Ridd et al., 2001). This type of sensor offers a significant advantage over traditional methods, being capable of measuring sediment accumulation with high temporal resolution (e.g. one measurement every hour) yet over long deployment periods of months. To illustrate the usefulness of the SAS, we show results from three field studies and demonstrate that short-lived events influence sediment accumulation but not necessarily in the expected manner. For instance high rainfall, followed by increased terrestrial runoff, observed at two sites, was found not to cause any increase in sediment accumulation rates. The fringing reef environments discussed are located in tropical waters at Ishigaki Island in Japan, Lihir Island in Papua New Guinea, and Magnetic Island in the Great Barrier Reef region, Australia. These sites were chosen because they all include fringing coral reefs along coastlines where anthropogenic development is taking place and where sediment accumulation could be a potential threat to coral health.

2. Material and methods

2.1. Sediment accumulation sensor

The SAS technique measures sediment accumulation by using the change in the optical response of an upward-pointing OBS to accumulating particles (Ridd et al., 2001). The OBS emits a vertical infra-red signal (wavelength of 900 nm) into the adjacent water column transmitted via a bundle of optic fibres (1 in Fig. 1b). These are interlaced with receiving fibres and as sediment particles accumulate on the OBS, the emitted signal is scattered in the accumulated particles and largely lost (2 in Fig. 1b). A small quantity of this signal, however, is backscattered, captured by the bundle of receiving optic fibres, and measured by a receiving photo-diode (3 in Fig. 1b). Broadly, the thicker the accumulated layer, the greater the backscatter signal strength. At regular intervals (e.g. every 5 min), the strength of the backscattered signal is recorded by the OBS logger as a raw uncalibrated output number. The SAS is equipped with a wiper (Fig. 1a) that automatically removes the accumulated sediment from the sensor at set regular intervals (e.g. every 30 min, or every six readings if the logging interval is 5 min), and causes a sharp fall in the next OBS output reading. The magnitude of this fall is related to the amount of sediment accumulated on the sensor since the previous wipe. That relationship is known with a 35% error margin from laboratory studies based on various sediment types,

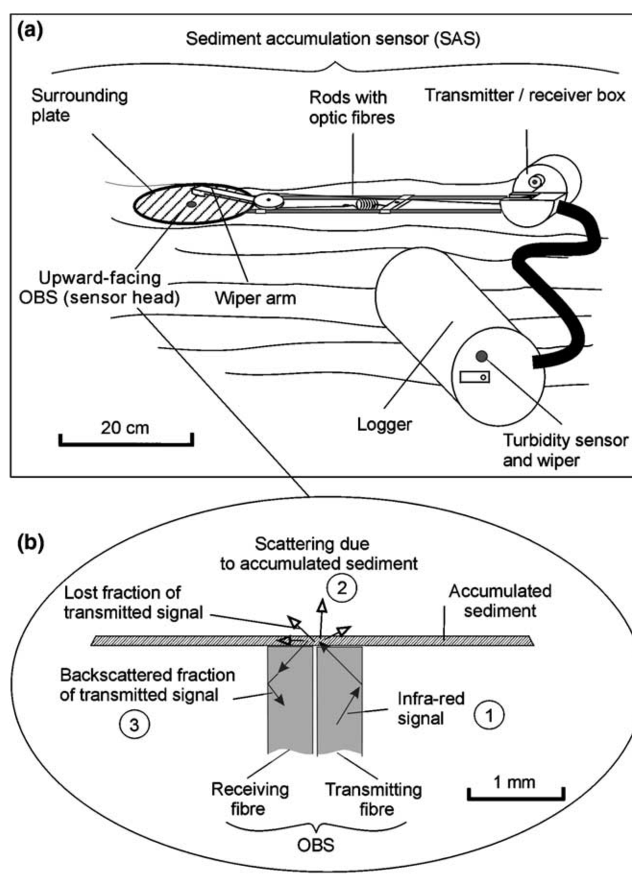

Fig. 1. (a) Sketch of the sediment accumulation sensor connected to its logger and (b) OBS operating principle of the SAS to measure sediment accumulation.

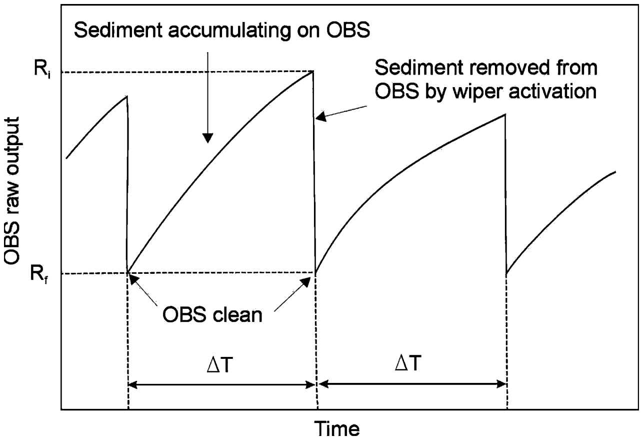

Fig. 2. Raw signal recorded by an upward-facing OBS under sediment accumulation. Each signal drop indicates accumulation between two wiper activations. ΔT is the wiper interval defined by the operator (from seconds to hours).

sediment size, sea-bottom types and current speed (Thomas et al., 2003a). The amount accumulated over a given area is expressed in accumulated surface density (in $mg\,cm^{-2}$), and is divided by the accumulation period (wipe interval) to yield an accumulation rate, generally expressed in $mg\,cm^{-2}\,day^{-1}$. Another unit commonly used is $mm\,year^{-1}$, which is directly related to the former one via the sediment density, but for consistency reasons, all results in this paper are presented in $mg\,cm^{-2}\,day^{-1}$. By recording a time-series of rises and falls of the OBS output (Fig. 2), the instrument provides a picture of sediment accumulation with a temporal resolution as high as minutes (depending on the wiping periods, which can be programmed from a few seconds to a few hours), and might cover deployment periods of weeks to months, limited only by battery life.

The instrument was designed to have minimal impact upon near-bed hydrodynamics, and to this aim the SAS sits flush with the sea or river-bed, and is connected to a separate logging unit so that no object protrudes significantly into the water column (Fig. 1a). It is noted that SAS results do not take into account any biological effect such as cilliary movement and stickiness of coral polyps, which can potentially modify the accumulation process over coral colonies by preventing accumulation (cilliary movement) and/or retaining settled particles (stickiness). Finally, the logger also records turbidity simultaneously to every backscatter reading based on a separate sideways-looking OBS.

2.2. Study sites

2.2.1. Ishigaki Island

Ishigaki Island is one of the Ryuku tropical islands at the southern extremity of the Japanese archipelago (Fig. 3a). The Todoroki River discharges into Shiraho Reef, a shallow fringing reef (1–4 m depth), 800 m in width, and

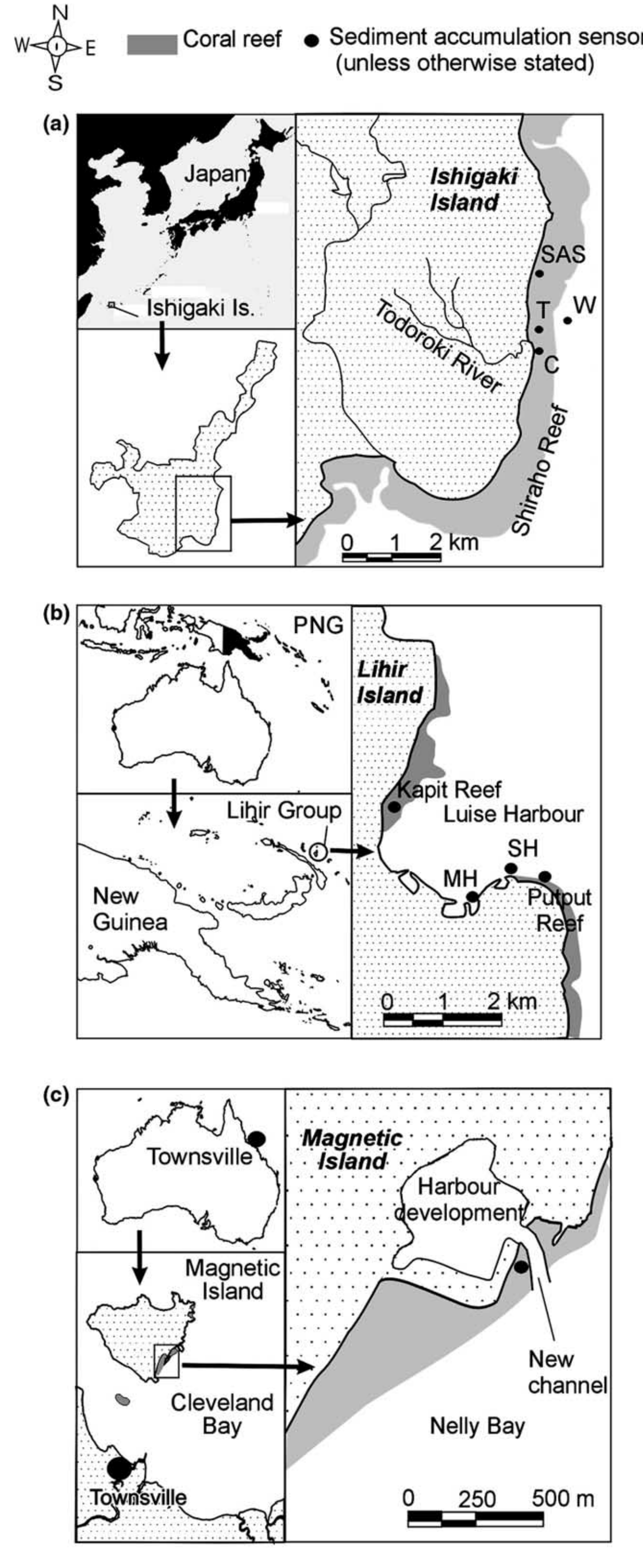

Fig. 3. Location of field sites at (a) Ishigaki Island (Japan), (b) Lihir Island (Papua New Guinea), and (c) Magnetic Island (Australia). SAS = sediment accumulation sensor, T = turbidity sensor, W = wave gauge, C = current meter. In (b), MH = Maintenance Harbour, SH = Small Harbour.

which hosts rare blue coral communities. The survey reported here was initiated by a projected airport development in the catchment of the Todoroki River and subsequent concerns about potential for increased sediment runoff and potential stress on the adjacent sensitive marine ecosystem. Nadaoka et al. (2001) and Nihei et al. (2002) present a complete overview of the hydrodynamics of Ishigaki Island. A range of instruments were deployed for one month in October 2000 as part of a baseline study including: wave gauge, current meter, turbidity sensor, tide gauge, river discharge gauge, and a sediment accumulation sensor. The accumulation sensor was deployed on the seabed, which was predominantly coarse sand.

2.2.2. Lihir Island

Lihir Island is an oceanic island located ≈100 km offshore New Ireland, Papua New Guinea (Fig. 3b). It is bordered by a shallow (≈4–8 m deep) and narrow (≈100 m wide) fringing coral reef bordering a steep drop-off. The east coast, where a gold mine is operating, is exposed to continuous high energy, oceanic swell waves. Mining operations are concentrated around Luise Harbour and include the disposal by barges of unprocessed sediment (topsoil or soil with too low an ore grade to process) in the bay, in areas with depths greater than 100 m (see Thomas et al., 2003b for information on surrounding turbidity regimes). Frequent rain also causes terrestrial runoff to discharge sediment into Luise Harbour, both directly via small creeks and indirectly via a settlement pond in the activity zone. The data presented here focuses on sediment accumulation, but it relates to a more comprehensive survey of sediment transport around Lihir Island in relation to mining activities (Thomas, 2003; Thomas et al., 2003b).

Four sediment accumulation sensors were deployed for up to three months inside and on the edge of Luise Harbour, i.e. near the center of the activity zone (locations called Maintenance Harbour and Small Harbour in Fig. 3b) and where coral reefs are found closest to the activity zone (Kapit Reef at the North and Putput Reef at the South in Fig. 3b). The sensors were deployed at 4–8 m depth on the seabed, except at Kapit Reef, where the SAS was deployed amongst coral colonies, raised from the seabed by ≈1 m in order to imitate the situation of surrounding colonies. The seabed was either a clay-rich mud substrate (Maintenance Harbour), coral rubbles and sand (Small Harbour), or coral reef (Kapit and Putput Reef).

2.2.3. Magnetic Island

Magnetic Island is an inshore island of the Great Barrier Reef, Australia, located ≈8 km from the mainland (Fig. 3c). The study site was located at Nelly Bay on the Southeast side of the island, which hosts a well-developed inshore fringing coral reef and where a new harbour was being developed at the time of the study (Fig. 3c). Larcombe et al. (1995), Orpin et al. (1999), and Orpin et al. (2004) describe the sedimentology, hydrodynamics and turbidity regimes in the region. The accumulation sensor was deployed for 5 months in 2002 as part of a monitoring survey around the new harbour development, of which a representative three weeks in September 2002 are discussed here. This includes a very windy period, which is not representative of average conditions but is of interest to model accumulation during high wave energies and represents the roughest conditions encountered by coral reefs locally, except maybe during rare cyclones. The sensor was located near the entrance of a newly excavated channel. No concurrent dredging work occurred during the deployment period discussed in this paper, which thus reports on accumulation rates under natural conditions near a man-made infrastructure (the new harbour). The turbidity and accumulation sensors were both deployed ≈30 cm above the seabed, in order to simulate the position of a coral colony.

3. Results

SAS records of accumulation rates comprise gaps in the data due to either fouling of the sensor, burial of the instrument by accumulated sediment under extreme accumulation conditions, or unreliable saw-tooth pattern in the signal mostly due to incomplete cleaning of the sensor by the wiper. Only the reliable sections of the datasets are presented here.

3.1. Ishigaki Island

3.1.1. Average accumulation rates

Accumulation rate of sediment (Fig. 4) over three months was 5 mg cm^{-2} day^{-1} on average with 45% of all data points below 2.5 mg cm^{-2} day^{-1}. Accumulation rate peaked above 20 mg cm^{-2} day^{-1} several times, with a maximum at 70 mg cm^{-2} day^{-1}. The longest continuous period above average lasted for approximately 48 h immediately preceding a typhoon (from day 253 until 255) but there is some uncertainty due to a gap in the data during that period. A threshold of 20 mg cm^{-2} day^{-1} was chosen arbitrarily to define an accumulation event, as it included most data points that were significantly different from the average level. All accumulation events were short-lived (2–4 h of increased accumulation).

3.1.2. Tidal influence on sediment accumulation

The accumulation record was studied in relation to the tidal data and Table 1 summarises all accumulation events and corresponding water depth. This table shows that accumulation increased overwhelmingly when

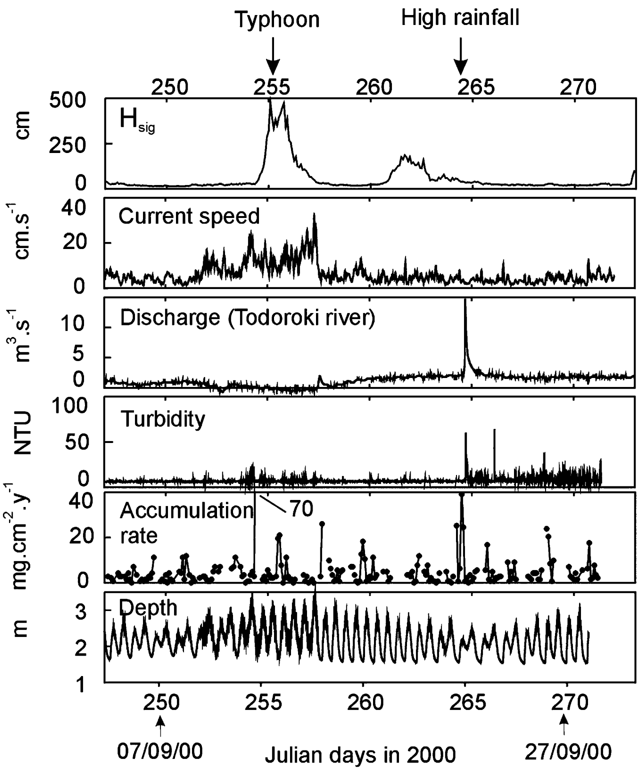

Fig. 4. Significant wave height (H_{sig}), current speed, river discharge, turbidity, sediment accumulation rate, and water depth at Ishigaki Island in September 2000. Discharge, wave, current, and tide data courtesy of Dr. Nihei from the Science University of Tokyo. Note that waves were recorded outside the reef lagoon on the deep ocean side, whereas other data were recorded inside the shallow lagoon.

Table 1
Accumulation event peaks and corresponding water depths at Shiraho Reef

Day in 2000	Accumulation event peak (mg cm^{-2} day^{-1})	Depth (m)
254.4	70	1.9
255.5	21	1.7
257.6	26	1.6
259.6	18	1.6
264.25	25	1.6
264.5	41	2.1
268.6	24	1.5

water depth was below 2 m, i.e. effectively at low tide. Accumulation events occurred both at spring and neap low tides, but not systematically at every low tide. Turbidity did not significantly increase during accumulation events. Current speed ranged 2–20 cm s^{-1} and waves ranged 20–500 cm before accumulation events.

3.1.3. Typhoon event

The highest accumulation rate of the deployment period (70 mg cm^{-2} day^{-1}) occurred on day 254 immediately after a current increase of up to 20 cm s^{-1}, but before the wave-height increased to 500 cm with the typhoon event. Accumulation rates increased a second time although less high (20 mg cm^{-2} day^{-1}) for 4 h during the peak of the typhoon (Fig. 4). It is noteworthy that such high accumulation rates also occurred at other times but under low wave and current conditions (e.g. on day 259 or day 264). Accumulation rates were low for the remainder of the typhoon event and such short-lived rises were not restricted to periods of large waves or fast current.

3.1.4. High rainfall event

On day 264, a high rainfall event occurred and the Todoroki river discharge increased sharply, followed by a sharp increase in turbidity in the lagoon (Fig. 4). Currents and waves were at low background levels during this period. Sediment accumulation rates peaked at 40 mg cm^{-2} day^{-1} on the same day for 6 h but this peak occurred prior to the discharge and associated turbidity increase (this is not a time-base error). Accumulation levels were back to low levels before the discharge started increasing.

3.2. Lihir Island

3.2.1. Average levels

Accumulation rates at Kapit Reef ranged 0–20 mg cm^{-2} day^{-1} (with one reading at 30 mg cm^{-2} day^{-1}) (Fig. 5). Accumulation rates at the Maintenance Harbour were usually between 0 and 20 mg cm^{-2} day^{-1}, with three main accumulation peaks of a few hours above 150 mg cm^{-2} day^{-1}. Rates were between 0 and 10 mg cm^{-2} day^{-1} at other locations, with peaks up to 100 mg cm^{-2} day^{-1} at the Small Harbour but at different times than other sites, and no major peak at Putput Reef (rates were almost continuously below 10 mg cm^{-2} day^{-1}). On-site observations revealed no significant sediment accumulation and no smothering on coral colonies at any of the sites where corals were present.

3.2.2. High rainfall event

On day 182, an extremely high rainfall event occurred, during which the discharge gauge measuring runoff from part of the mining area near Kapit Reef recorded a discharge increase from less than 1 m^3 s^{-1} to 12 m^3 s^{-1}, followed by a high discharge for the following four days (Fig. 5c). This event caused an increase of the suspended sediment concentration (SSC) in the discharged waters from 30 to 150 mg l^{-1} (SSC data shown in detail in Thomas, 2003) and accumulation increased at the Maintenance Harbour gradually over 12 h from ≈10 up to 100 mg cm^{-2} day^{-1}, with a maximum at 200 mg cm^{-2} day^{-1} (Fig. 5c). The accumulation rate fell to 10 mg cm^{-2} day^{-1} 24 h after the peak discharge. No accumulation increase above background levels occurred at the Small Harbour (500 m East of the Maintenance Harbour), nor at Putput Reef on the coral reef

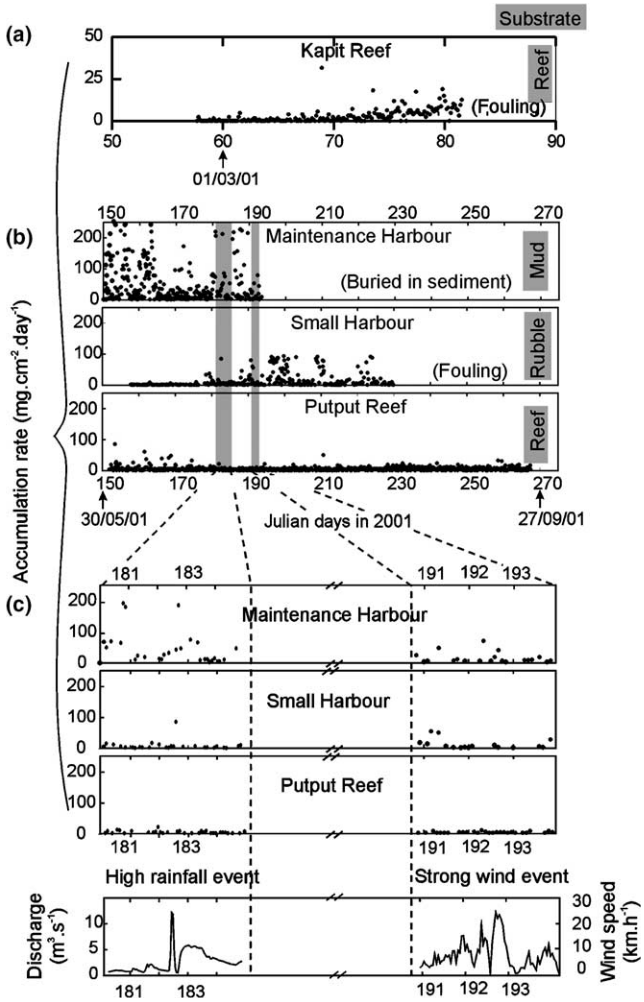

Fig. 5. Sediment accumulation rates at Lihir Island (a) in March 2001 at Kapit Reef and (b) in June–September 2001 at other locations with (c) details of a rainfall event and a strong wind event. Average accumulation rates near reefs are between 0 and 10 mg cm^{-2} day^{-1}, and strong wind and high rainfall events did not cause significant increase in accumulation rates near reefs.

living nearest to the activity zone. There is no simultaneous data available at Kapit Reef. However, data recorded during three other high rainfall periods show that that there was no accumulation increase subsequently to these three runoff events, with discharge up to 8 m^3 s^{-1} (Thomas, 2003). An 8 m^3 s^{-1} peak discharge represents two thirds of the largest above mentioned event on day 182, which reached a 12 m^3 s^{-1} discharge, and it is thus considered to be a good indication in terms of sediment accumulation response to high rainfall.

3.2.3. Strong wind event

On day 192, southerly wind increased up to 30 km h^{-1} and was sustained in two bursts for several hours (Fig. 5c), whilst no rainfall occurred at that time nor had occurred during the previous four days at least. The consequent response of the wind event was a large increase in SSC at the Maintenance Harbour (up to 500 mg l^{-1} versus average levels of ≈30 mg l^{-1}) (see Thomas (2003) for detailed SSC data). In contrast, an almost insignificant increase occurred at the Small Harbour (up to 40 mg l^{-1}), and no increase occurred at Putput Reef. During this event, accumulation increased at the Maintenance Harbour from <10 mg cm^{-2} day^{-1} to >50 mg cm^{-2} day^{-1}, whilst it remained low at Putput Reef, the closest living reef location. A gap in the accumulation record at the Small Harbour precludes any comparison with this location.

3.3. Magnetic Island

The accumulation sensor record did not show any saw-tooth pattern with the wiper period (as in Fig. 2), other than for about 30 min on six occasions over the five months deployment. Hence, the accumulation data of the survey from Magnetic Island is presented in equivalent nephelometer turbidity units (NTU) instead of an accumulation rate (in mg cm^{-2} day^{-1}) and the accumulation sensor was considered to operate as a traditional OBS turbidity sensor (Ridd and Larcombe, 1994). It can be observed in Fig. 6a that, although both accumulation and turbidity records display the same baseline, the former is significantly noisier than the latter. The noise was particularly high during a strong wind event that occurred on 12–14 September 2002 with sustained easterly wind speeds above 30 km h^{-1} (Fig. 6b). The noise in the accumulation record is caused by the accumulation sensor facing upwards (whilst the turbidity sensor was facing sideways), thus allowing particles to deposit on the sensor. However, the drop of output level, which occurred independently of the wiper period and caused the noisy-looking record, indicates that these deposited particles were resuspended within minutes of settling. As a consequence, no net accumulation resulted from this process.

4. Discussion

4.1. Ishigaki: investigations on the influence of short-lived events on sediment accumulation

Comparison of peaks in accumulation rate and tidal stage at Ishigaki Island suggests that low water is a prerequisite for the accumulation rate to increase, but not a sufficient forcing factor. Tidal currents do not seem to be the trigger for accumulation to increase, and no resuspension was recorded by the turbidity sensor deployed 40 cm above the sediment/water interface. Because of this lack of parallelism between accumulation rate and turbidity, and because of the coarse grain size on site, it is thought that the SAS recorded the movement of sand particles by saltation across the sensor.

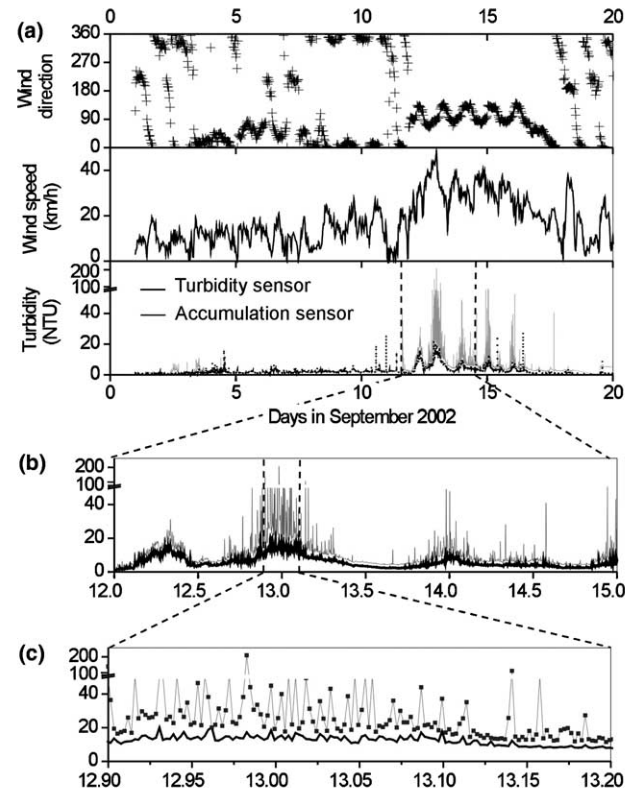

Fig. 6. Magnetic Island SAS and turbidity sensors data with wind speed and direction in September 2002. (a) SAS data is shown in NTU because no accumulation sawtooth pattern was present in the record. (b) and (c) Details of the record during a strong wind event, illustrating the noisy on the SAS record due to reworking of sediment but resulting in no net accumulation.

Hence, at low water levels, particles seem to be resuspended by wave action (even as small as 20 cm) just above the seabed into the boundary layer, but not to be lifted into the water column. These particles would then drift onto the accumulation sensor and redeposit, but would not increase the turbidity level as recorded by the turbidity sensor because the sand grains are only mobilised close to the bed.

High waves and currents associated with the passage of a typhoon do not seem to have caused increased accumulation rates. Instead, the signals recorded appear to be influenced by the intrinsic variability of local processes. Similarly, high accumulation rates are not necessarily associated with high turbidity levels, and vice-versa. Results during the high rainfall event suggest that the sediment flushed out by the Todoroki River did not accumulate on Shiraho Reef ≈1.5 km north of the river mouth. A possibility is that the sediment carried by the river preferentially accumulates within a restricted radius seaward of the estuary. Visual observations on site did not reveal any terrigenous sediment even in the first 100 m seaward of the estuary. However, this does not rule out the possibility of local accumulation as sediment could be deposited temporarily by the runoff event and be dispersed gradually by other mechanisms, such as tides. Alternatively, during the peak of the river discharge, when the estuary lies seaward of the river mouth, the zone of sediment accumulation may be located offshore on the innermost shelf, and sediment may not be transported longshore onto Shiraho Reef. A scenario of rapid export of sediment flushed out by the river is more likely than a slow dispersion, which would almost certainly leave some traces of terrigenous sediment near the estuary (and no such trace was found). In any case, high rainfall and increased river discharge did not cause increased accumulation at the observation site.

In conclusion, accumulation rate and turbidity measurements at Shiraho Reef did not reveal any significant variations in sediment accumulation near coral colonies directly related to a high river discharge event or a typhoon event. Accumulation rate patterns and levels did not change significantly with higher waves, stronger currents, larger discharge, or more turbid water than average. Although general conclusions are not possible because only one of each event occurred (high rainfall and typhoon) and only one site was surveyed, the main control of increased accumulation seemed to be tidal height, causing reworking of sediment by waves, even when small. It is noteworthy that these results could not have been obtained with conventional techniques like sediment traps, even with a very labour-intensive daily recovery of the traps.

4.2. Lihir Island: an example of management application of the SAS with characterisation of impact zones

Accumulation rates were combined with an extensive turbidity dataset to determine impact zones in shallow waters (<10 m) around Luise Harbour (Thomas et al., 2003b). Impact zoning is a tool used in environmental management to assign a level of impact over different areas, usually where anthropogenic disturbance has occurred or may have occurred, by integrating various parameters such as water quality characteristics, and fauna and flora information (but it can also include social, economical, or other parameters). In our study, impact zones were defined from a point of view of potential impact by sediment on corals, and were thus practically circumscribed based on the accumulation rate and turbidity records. The correspondence between impact zone and accumulation rates is shown in Table 2. Median turbidity of month-long records are also shown as they were used to define the spatial limits of impact zones.

Beyond this local analysis of impact zones, drawing robust comparison of the observed rates versus reference rates with a view to assess the potential impact of sediment accumulation over coral reefs is an ambitious exercise. The concept of a sedimentation threshold, above

Table 2
Accumulation rate levels corresponding to impact zones at Lihir Island and median SSC in each zone

Impact zone	Accumulation rate ($mg\,cm^{-2}\,day^{-1}$)	Median SSC ($mg\,l^{-1}$)
Severe	25 and 50 $mg\,cm^{-2}\,day^{-1}$ with large internal variations (Maintenance Harbour)	>30
Transitional	10–20 $mg\,cm^{-2}\,day^{-1}$ (lower rates were also measured at location A but for a conservative approach, only the highest value is retained) (Kapit Reef and Small Harbour)	15–30
Minor	5–10 $mg\,cm^{-2}\,day^{-1}$ (Putput Reef)	5–15
Background	1–2 $mg\,cm^{-2}\,day^{-1}$ (from baseline study (NSR, 1996))	<5

which some proportion of a species will suffer mortality, is a useful one both for setting environmental standards for management and for discussing the natural environmental controls on species distributions. However, the variable nature of sediment regimes, the range of coral reef habitats, and the diversity of its inhabitants, mean that this goal is not simple to achieve (Stafford-Smith, 1992). Tables 3 and 4 review published examples of in situ accumulation rates around the world for natural and impacted reefs respectively. These rates were measured with sediment traps except for two studies (McClanahan and Obura, 1997; Lasker, 1980), which are thus expected to differ from measurements taken with the SAS (mostly due to the hydrodynamics disturbance caused by traps) and from what actually falls on a particular type of coral.

Table 3 shows range of <1 to >200 $mg\,cm^{-2}\,day^{-1}$ measured in natural reef conditions. On the other hand, Table 4 shows that adverse conditions are reported to start with accumulation below 10 $mg\,cm^{-2}\,day^{-1}$. Stafford-Smith (1992) reports a sedimentation threshold of 25 $mg\,cm^{-2}\,day^{-1}$ for coral to be adversely affected and observed tissue damage from accumulated sediment thickness of 1–1.5 mm (≈160 $mg\,cm^{-2}$), provided the sediment cover remained for at least 3 days. Randall

Table 3
Review of sediment accumulation rates measured over reefs experiencing no impact from anthropogenic activity

Accumulation rate ($mg\,cm^{-2}\,day^{-1}$)	Location	Additional information	Reference
<1 to 30	Puerto Rico, Caribbean	*Acropora cervicornis*, *A. palmata*, *Monsastraea annularis*, *Diploria strigosa*, *D. clivosa*	Rogers (1990)
0.45–1.1 6–19 including resuspension	Jamaica	Numerous species No information on stress	Aller and Dodge (1974)
19.9	Florida	Control site	Marszalek (1981)
27	GBR, Cape Tribulation	Numerous species control site	Hoyal (1986)
30–120	GBR, Magnetic Island[a] (Nelly Bay and Geoffrey Bay)	On reef slope *Acropora latistella*, *Merulina ampliata*, *Montipora aequituberculata*, *Pocillopora damicornis* dominating	Collins (1987)
1–267 80 5.3	GBR: Magnetic Island[b] Geoffrey Bay Picnic Bay	*Acropora latistella*, *Merulina ampliata*, *Montipora aequituberculata*, *Pocillopora damicornis* dominating	Babcock (1986)
9–62 15 (4-months mean) 6–40	GBR: Middle Reef (Magnetic Island[b]) Rattle Snake Island		Woolfe and Larcombe (1998)
3–180	GBR: Low Isles	Growing reefs Numerous species	Marshall and Orr (1931)
3[c]	Watamu (Kenya)	Control, coral cover increasing *Montipora*, *Pocillopora*, *Astreopora and Favites* dominating	McClanahan and Obura (1997)
0.3–37 0.1–228	Caribbean Indo-Pacific	Wide range of species	Pastorok and Bilyard (1985)
0.5 on living corals[b] 4 on dead ones	Caribbean	*Montastrea cavernosa*	Lasker (1980)

[a] Location is considered by some authors to suffer an impact from a century of channel dredging.
[b] In situ collection of accumulated sediment with syringe.
[c] Measured with tiles and corrected to have equivalent settling tube rate (rates multiplied by 3).

Table 4
Review of sediment accumulation rates measured over reefs experiencing some impact

Accumulation rate ($mg\,cm^{-2}\,day^{-1}$)	Location	Additional information	Reference
200 400 800	Caribbean, Puerto Rico	Death *Acropora palmata* *Acropora cervicornis* *Montastraea annularis*	Rogers (1979)
13 to >500, median 65, average 152	Puerto Rico	Impact from river runoff in timber-cleared area; stress if rate maintained >30	Cortes and Risk (1985)
38.2 dredged site (siltation events an order of magnitude higher)	Florida	Loss of zooxanthellae, polyp swelling, excessive mucus secretion Numerous species	Marszalek (1981)
86 near old road, 129 near new road	GBR, Cape Tribulation	Sedimentation increase caused by higher sand erosion in new road area	Hoyal (1986)
9–12	Malindi (Kenya)	Site influenced by soil erosion but no impact detected *Porites*, *Galaxea*, *Exhinopora*, *Fydnophora*, *Millepora* and *Platygyra dominating*	McClanahan and Obura (1997)

and Birkeland (1978) produced graphs indicating coral species richness, percentage cover and colony size as a function of sedimentation rates measured over extended periods in natural coral reef habitats. Examination of their results suggests that, at least for total coral species and for percentage coral cover, there may be an important threshold at about $150\,mg\,cm^{-2}\,day^{-1}$. Pastorok and Bilyard (1985) presented a classification of degree of impact, based on their own and others' data that indicate a threshold as low as $1\,mg\,cm^{-2}\,day^{-1}$ for slight impact, and $10\,mg\,cm^{-2}\,day^{-1}$ for moderate impact to occur. Mapstone et al. (1989) note that these thresholds may be over conservative. Pastorock and Bilyard's thresholds are also contested by Larcombe et al. (2001). Finally, Cortes and Risk (1985) define terrigenous stress with a sedimentation rate greater than $30\,mg\,cm^{-2}\,day^{-1}$.

In view of these values and comments, and since smothering or burial of coral was not observed on site, corals in the transitional, minor and background impact zones along the Lihir Island east coast are unlikely to be impacted by sediment accumulation. This is largely explained by the persistent swell all along the coast. If present, corals would have been highly likely to be impacted in the severe impact zone, where accumulation rates are much higher than elsewhere by a factor of $\approx$10, however there are no corals (alive or dead) in this zone.

When looking at the influence of high rainfall over accumulation rates at Lihir Island, the SAS record indicates that sediment accumulation after a high rainfall event increased inside the Maintenance Harbour, near the surface runoff outlets, which exit inside the Maintenance Harbour. No more sediment appears to have accumulated on the nearest reefs than under average conditions, probably because sediment accumulated mostly inside the Maintenance Harbour, a relatively sheltered area, and was not available for accumulation over the reef at Putput Reef.

During the strong wind event, SSC increased simultaneously to accumulation rates recorded in the Maintenance Harbour, which suggests that local resuspension occurred. This dataset also suggests that the resuspended material is more likely to resettle without being significantly dispersed, since no increase in SSC or accumulation rate was recorded at other locations (this survey and Thomas, 2003). In particular, this event shows that resuspension of material by a southerly wind is not likely to impact fringing reefs south of Luise Harbour.

In this application, SAS were used to put average accumulation rates in perspective of impact zones related to mining activities around coral reefs, and to characterise these impact zones including the variability of accumulation with various forcings in each zone.

4.3. Magnetic island: an atypical use of the SAS to detect resuspension

At Magnetic Island, the sediment resuspended during the strong wind event was not observed to settle on the SAS. We suggest that the resuspended material was probably flushed out by northward longshore currents, which are driven both by tides (Larcombe et al., 1995) and southeasterly trade winds during the dry season from April to November (Orpin et al., 2004). No sediment appeared to have settled on the 30 cm high SAS plate, and by inference not on coral colonies that live at more than 30 cm above seabed level as well. Hence at this site, we suggest that accumulation on reef colonies is a rare event despite the fact that this reef exists in moderately turbid waters ranging from 0.1 to over 100 NTU during strong wind events (Orpin et al., 2004).

During such an event, a sediment trap would have probably yielded a significant net accumulation rate because it would have created a calmer zone within the trap, hence preventing sediment resuspension and dispersion, and promoting particle settling, contrary to the surrounding conditions. Therefore, the strong wind event would have probably been associated with an accumulation peak if a sediment trap had been used to measure sediment accumulation, whilst in fact the event seems to have only resuspended and reworked surrounding sediment, but not caused net accumulation. The use of the SAS in this case gives a unique opportunity to detect resuspension processes in a non-accumulative environment, even though the instrument was primarily designed to quantify positive accumulation rate.

5. Conclusion

The new sediment accumulation sensor (SAS) allows potential identification of the processes leading to sediment accumulation with appropriate measurements on short-term variations (order of an hour) linked to river discharge, current, wave, tidal regimes, and any other short-term natural or artificial parameter. It can also provide in situ field data regarding the delivery and removal mechanisms of sediment, and detect non-accumulative environments although it cannot be used to quantify erosion. Accumulation rates were thus observed not to be directly related to suspended sediment concentration, since each of these parameters was seen to increase independently of the other. Examples presented in this paper focused on coral reefs and average rates were recorded to be mostly below $10\,mg\,cm^{-2}\,day^{-1}$, with peaks rising to 50–100 $mg\,cm^{-2}\,day^{-1}$ and short-lived, lasting in the order of 3 h. Despite this focus on coral reefs, the use of the SAS instrument is not restricted to reefs but it may be used in a variety of environments, such as mangrove swamps, estuaries, beaches, mudflats, harbours, manmade settling ponds, or any underwater environment where detailed sediment accumulation measurements are required. Practically and in view of future use of the SAS, it is important to ensure that the wiping period is below the time scale of the forcings that are investigated, both to allow good temporal resolution and to avoid electronic saturation when the accumulated layer becomes too thick. A wiper interval of 15–30 min was found to be adequate in most field studies.

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